Design and Analysis of Gear Box Test Bench to Test Shift Performance and Leakage

S.S.Khodwe[1], S.S.Prabhune[2]

[1]Research scholar ME student, Department of Mechanical Engineering,
Maharashtra Institute of Technology, Pune, Maharashtra, India
[2]Professor, Department of Mechanical Engineering, Maharashtra Institute of Technology, Pune, Maharashtra, India

ABSTRACT

Transmission is one of the critical and most important systems of an automobile and it largely affects the driving performance, safety and riding comfort of the vehicle. Gearbox is an important element in power transmission drives of most of the mechanical systems. Therefore, it is important to ensure the performance of gearbox prior to its usage in actual systems. The performance of gearbox should be tested to ensure the trouble free functioning of gearbox. There are various tests that should be performed on the gearbox to ensure its working performance which includes shift performance test, leak test and noise test. Gear shifting mechanism is link between driver and vehicle. The shift force is an essential criterion for the operating quality of gear shift. Gearbox noise is sometimes the dominating noise in commercial vehicles which has to be minimum. Leakage from gearbox is also one of critical problem. This work presents the design of a test bench for gear box to test a gearbox at the end of assembly line to check leakage, noise, gear shifting feeling and shift load in driving and dragging condition. This includes design of fixture for gearbox, clamping arrangement, gear shifting arrangement, design of oil dispensing, extraction and filtration unit. Also the FEA of fixture components has been carried out.

Keyword: - *Gearbox, Design, Clamping, Oil dispensing-extraction-filtration unit, FEA*

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1. INTRODUCTION

Gearbox is an important element in many mechanical systems such as automobiles, cranes and machinery. Now a day's gearbox is used almost everywhere. Basic function of gearbox is to increase or decrease the torque effectively as per requirement. The main function of automobile gearbox is to transmit the torque and motion between prime mover and driven pieces of automobile at acceptable level of noise, vibration and temperature. During this operation, while gear is being shifted, gear shifting lever should travel a specified distance and travel of gear shift lever should be smooth. Automobile gearbox contains gearbox oil. Hence during the operation of the gearbox, there should not be any kind of oil leakage. If any of above prescribed parameters exceeds specified range, gearbox will not work properly. Hence before putting any gearbox in operation it is very essential to check its performance.

2. LITERATURE REVIEW

In the design of test rig, fixture is an important part, as it holds the component on which tests are going to be performed. Fixture has direct impact on cost and productivity; hence much attention needs to be given to fixture designing. Hui Wang, Yiming Rong, Hua Li and Price Shaun [5] in their work describe the computer aided fixture design (CAFD) and automation in this field over past decades. They have given detail application of fixture in industry. Different types of fixtures are studied; basic elements of fixture designing techniques are also discussed. In their work they have also discussed FEM based fixture design solution and analysis frame work along with the study related to overview of fixture verification system.

NOMENCLATURE

a	:	Length of plate (mm)	k_b	:	Equivalent shock factor
A	:	Total area of plate (mm^2)	k_t	:	Equivalent fatigue factor
b	:	Width of plate (mm)	L	:	Length of shaft (mm)
C	:	Dynamic capacity (kg/mm^3)	L_{10h}	:	Basic rating life (cycle)
d_1	:	Diameter of Input shaft (mm)	$L_{p'}$	:	Approximate belt circum length (mm)
d_2	:	Diameter of output shaft from gearbox (mm)	M	:	Maximum bending moment (N-mm)
d_3	:	Diameter of output shaft (mm)	M_e	:	Equivalent bending moment (N-mm)
d'	:	Boar diameter of clamping cylinder (mm)	P	:	Power rating (kW)
d''	:	Diameter of tandem cylinder (mm)	P_1	:	Load acting on the horizontal plate (N)
d_p	:	Diameter of small pulley (mm)	p	:	Load (N)
D_p	:	Diameter of small pulley (mm)	t_1	:	Thickness of horizontal plate (mm)
E	:	Young’s modulus (N/mm^2)	t_2	:	Thickness of horizontal plate (mm)
F	:	Total load carried by shaft (N)	t'	:	Thickness of weld (mm)
F_R	:	Radial force (N)	T	:	Torque (Nm)
h	:	Height of key (mm)	w	:	Width of key (mm)
h'	:	Height of weld (mm)	W	:	Force at the centre of free edge on the vertical plate (N)
I	:	Moment of inertia (mm^4)	y_{max}	:	Maximum deflection (mm)
J	:	Polar moment of inertia (mm^4)	τ_{max}	:	Maximum shear stress (N/mm^2)

Suhas Mohite, Rahul Shinde and Amruta Lomate [8] in their work describe a design and development of torque test rig for gearbox. They have designed the torque testing test rig for 0.5-10 kNm torque carrying capacity, carried out for gearbox having multi plate break system. They have compared theoretical calculations with experimentally measured data and calibration of test rig is done.

V. Manoj, K. Gopinathan and G. Muthuveerappan [10] developed power recirculating test rig to check performance of gears. This test rig has one pair of spur gear on which tests are performed and another pair of helical gears which act as loading gear. Here axial loading of helical gear is achieved with the help of pneumatic actuator which results in variation in gear loading. At starting no load condition, hence size of a motor is reduced and design is cost effective. Condition monitoring on test rig is performed. The designed test rig is equipped with computer data acquisition system.

Mats Akerblom [9], has developed test rig to test gears at controlled operating conditions. The test rig is of power recirculating type. He has performed finite element analysis to find dynamic properties of test rig. To find out natural frequency of gearbox housing, modal analysis is carried out.

In the proposed design of test bench all the three tests will be carried out on the same machine. During the operation gearbox is to be filled with the oil and after performing test this oil should be drained out from the gearbox. Hence to perform all these function, oil dispensing filtration and extraction unit is designed. In this work, the concept of test rig is developed which will test the gearbox at the end of assembly line. As there are various tests carried out on a single machine, the test rig is thus called as test bench. The parameters which will be tested are-

- Leakage test (dry leakage test).
- Shift force test in forward condition and noise test
- Shift force test in dragging condition and noise test.

The proposed system is equipped with computer data acquisition; the operations performed by machine are controlled by SCADA. Different types of test rigs which are used to test various parameters are available in the market are studied. Each test rig has its own advantages and disadvantages.

3. METHODOLOGY

According to the given input parameters and parameters by which we are going a gearbox, four options are made. The best suited option shown in figure 1 is selected. The main components of this proposed test bench are motors, fixture for mounting a gearbox, clamping arrangement for gearbox, gear shifting arrangement, timing belts for transmission of power and oil dispensing-filtration and extraction unit to fill the oil in the gearbox during its run time and also to extract the oil from the gearbox after all tests have been performed.

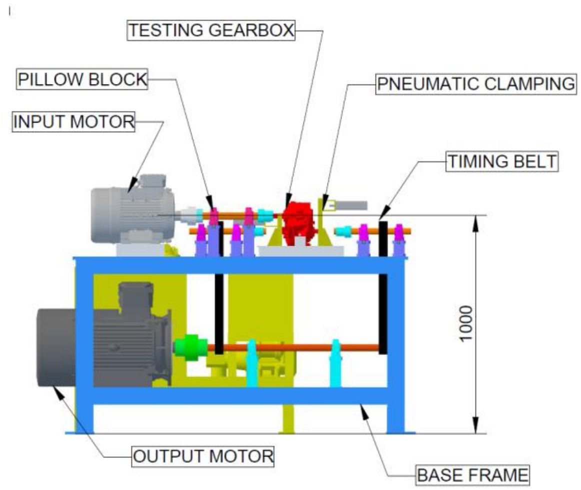


Fig -1: Outline of proposed gearbox test bench (F.V)

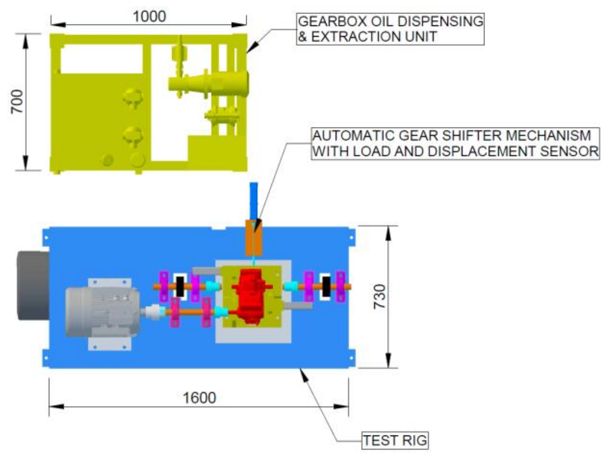


Fig -2: Outline of proposed gearbox test bench (T.V)

4. DETAIL DESIGN OF COMPONENTS

As per the above conceptual design the main test bench is divided into number of sub systems which are carrying some specific function. These sub systems are as follows

4.1 Fixture Designing for Test Bench

Here designing of input shaft, output shaft and shaft from gearbox output, coupling selection, selection of pillow blocks, selection of c channel for mounting plummer blocks, timing belt selection is described as follows:

1) ***Motor selection:*** Motor is required for providing torque to the gearbox need motor. Input data given is as follows. Input to output ratio is given to be 1:11, hence at output, motor torque will increase and rpm will decrease. From the given input parameters, power for input and output motor is found out as 7.5kw and 22.5kw. Here, servo motors are being used on both output and input side, because of its high torque carrying capacity, position and breaking control.

Table -1: Parameters for Selection of Motor

Parameter	Value	Unit
Input motor rpm	3000	rpm
Input torque	20	N-m
Output motor rpm	750	rpm
Output motor torque	220	N-m

2) ***Shaft design:*** Material for shaft is selected as C40 [1], Shafts are designed for torsional loading. Maximum shear stress theory is used to find the diameter of shaft because material selected is ductile. Test bench

should have long life; hence we have taken factor of safety as 6. For more safe design we designed shaft for torque of 50 N-m. Shafts are designed by using ASME code and diameters obtained are given in table 2. These shafts are step shafts with step of 2.5 mm both sides. Step shaft provides proper location bearing and because of that the bearing will not slide along the length. Shaft which is connected to the output of gearbox is provided with hexagonal shape; because when doing assembly operator are not supposed to disassemble each component, by sliding a coupling on shaft side only gearbox can be taken out.

Table -2: Calculated Shaft Diameters

Shaft	Length (mm)	Torque (N-m)	Label	Diameter (mm)
Input	400	50	d_1	45
Intermediate	500	210	d_2	50
Output	1200	210	d_3	50

3) ***Coupling selection:*** Plastic couplings are used because these couplings are easily available and they are cost effective. Selecting HYDAX-48 and HYDAX-65 coupling. For ease in assembly intermediate shaft is provided with hexagonal shape at one end. Because of this provision coupling can easily slide on the shaft, it is fitted with the help of nut.

4) ***Bearing blocks (plummer blocks) selection:*** For ease in assembly plummer blocks are used. Bearings are selected by calculating dynamic capacity. Calculated dynamic capacity is compared with the dynamic capacity of bearings available in catalogue and if calculated dynamic capacity is less than the dynamic capacity of bearing in catalogue, then that bearing is selected. Selected plummer blocks are given in table 3.

Table -3: Selected Plummer Blocks

Shaft	Value of p (N)	L_{10} (cycles)	Calculated C (N) $=p(L_{10})^{1/3}$	Selected Bearing
Input	1318.179	2160	17039.58	SYJ45TF
Intermediated	724.306	2160	9362.83	SYJ50TF
Output	1283.483	540	10109.70	SYJ50TF

5) ***Timing belt selection:*** For transmitting power from gearbox output shaft to the output drive shaft we are using timing belt. Timing belts have tooth and these tooth get engage with the tooth of the pulley and there is less noisy transmission of power. For selecting timing belt we are using standard MISUMI catalogue. Here the transmission ratio is given to be 1:2 and hence, we have to transmit 220N torque at 750 rpm and centre distance between the two shafts is 550 mm. From the catalogue we select S8M belt with belt width of 60mm. Number of teeth on small and large pulley are calculated as 20 and 40.

6) ***Designing fixture for gearbox:*** For resting the gearbox, we need to provide a fixture. There are three components in the fixture, namely resting blocks, nylon pads and fixture plate, which will support the resting blocks and nylon pads. Resting blocks are provided to place gearbox in specific position. Gearbox is to be placed at an angle of 30 degree with horizontal. Hence, height and widths are adjusted accordingly. Resting blocks are made of nylon. Nylon is used because it will absorb vibrations which will be produced by gearbox in working condition. Resting blocks and nylon pads are to be held in position, hence fixture plate is provided. It will give support for resting blocks and nylon pads. Fixture is made of three plates, one is base plate and other two are vertical plates which are welded to the base plate. Hence, for deciding thickness of the plate, we have to design a plate. For fixture C40 material is selected [1]. Here σ_{max} is 135 N/mm^2. Calculations for deciding thickness of two plates are shown in table 4.

Two main plates of fixture are joined together by welding, it’s important to analyze the weld joint. Here we find the width and height of the weld. The permissible shear stress for welded joints is 95 N/mm^2 for static load and 35 N/mm^2 for reversed load. Load of 176.58 N is acting at a distance of 235 mm from base one plate. Let, t' be the thickness of weld, h' is height of weld. Total area where welding is done is 2(250 X t') =

500t'. Calculations to decide welding dimensions are given in table 5. Model is created using Geomagic design software as shown in figure 3.

Table -4: Fixture Plate Calculations

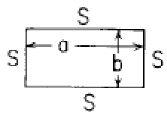
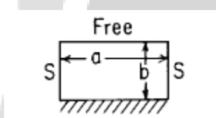
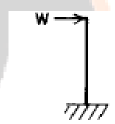
Plate	Shape and support	Loading	Formula Used	q(N/mm) and w(N)	α, β	a, b (mm)	t, y_{max} (mm)
Horizontal Plate	Rectangular plate; all edges simply supported 	Uniform over entire plate	At centre $\sigma_{max} = \frac{\beta q b^2}{t^2}$ $y_{max} = \frac{-\alpha q b^4}{E t^3}$	q(N/mm) udl on plate Weight of gearbox is uniformly distributed over the area q= 0.1855 N/mm	From catalogue α=0.77 β= 0.046	a= 370 b= 300	t=15 y_{max}= -0.08
Vertical Plate	Rectangular plate; one edgefixed, opposite edges free, remaining edges simply supported 	distributed line load w lb/ in long the free edge 	At the centre of free edge $\sigma_{max} = \frac{\beta^2 w b}{t^2}$	w = force at the centre of free edge (N) Force at the centre of free edge on the plate W= 315.58 N	From catalogue β= 1.868	a= 300 b= 265	t = 20

Table -5: Calculations for Weld Dimensions

Primary shear stress (N/mm^2)	τ_1= (P/A) = 176.58/t'
Bending stress (N/mm^2)	$\sigma_b = M_b / I = 0.01593 / t'$
Maximum shear stress (N/mm^2)	$\tau = \mathrm{sqrt}\,[\,(\sigma_b/2)^2 + (\tau_1)^2\,]$
Let height of weld be 3mm, hence t' = 0.707h' = 2.121 mm Putting this value in maximum shear stress	
Maximum shear stress	τ= 0.166 N/mm^2 < 95 N/mm^2 (safe)
Hence, t'= 2.121 mm	

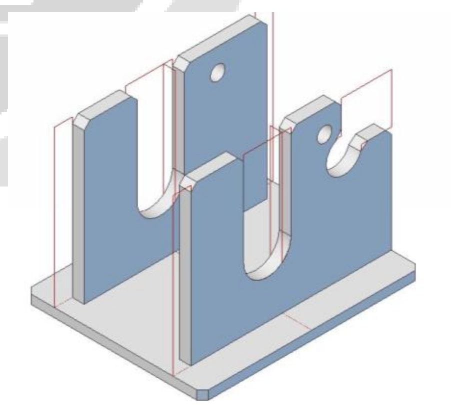


Fig -3: Fixture model

4.2 Clamping Arrangement for Gearbox

To fix the gearbox on fixture, clamping arrangement is provided. Pneumatic cylinder is used for clamping. Input parameters for calculations are given in table 6 and calculations for finding bore are given in table 7. Here we are selecting camozzi 25 series with boar of 200 mm. This cylinder is fixed to the fixture with the help of bracket.

Table -6: Input Parameters for Clamping Cylinder

Parameter	Value	Unit
Outside diameter of clamping area	2.54	cm
Inner diameter of clamping area	1.35	cm
Test pressure	4	bar
Supply pressure	4	bar

Table -7: Input Parameters for Clamping Cylinder

Parameter	Equation	Value
Outer area of clamping	$(OD)^2 * 0.7854$	4.5 cm^2
Force on the clamping area	Outer area * test pressure	18 kg
Force	Pressure * Area	
	$18 = 4*\pi\, r'^2$	
	r'	11.968 ~ 12 mm
	d'	24 mm

4.3 Gear Shifting Arrangement

Gear shifting is done with pneumatic tandem cylinder. This cylinder is multi position cylinder. In the test shifting force should not be more than 15 kgf, hence we will design for 20kgf. Now let pressure for shifting is 5 bars. By calculations boar of the cylinder is calculated, d"= 25 mm. The cable is attached to the cylinder stroke and to the load cell and then it is connected to the gear shifting lever. S type load cell is used it can measure load, both of push and pull type. Here maximum force limit is given to be 15kgf, hence we have selected standard load cell of HBM having capacity of 20 kgf. It is calibrated in the range of 4 – 20 mA output to PLC i.e. 4 – 12 mA for pull and 12 – 20 mA for push.

4.4 Oil Dispensing Filtration and Extraction Unit

During the operation, gearbox is to be filled with clean oil and after the operation this used oil is to be drained out from the gearbox and it should be filtered. 700 ml of oil is to filled in the gearbox, there nearly 40 gearbox per day, hence 28 liter oil is to be needed. As per standard procedure we have to design a tank for double size, also we have to consider oil left in filters hoses etc. Hence tank capacity is 100 liters. From company standards tank dimensions and thickness are selected as given in table 8.

Table -6: Tank Specifications

Parameter	Value	Unit
Storage volume	100	Liter
Actual volume	145.8	Liter
Length	600	mm
Width	540	mm
Height	750	mm
Thickness	1.6	mm
Weight	22.72	Kg

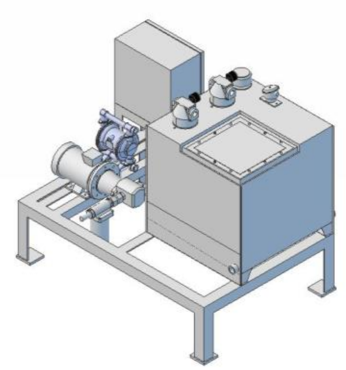


Fig -4: Oil dispensing, filtration and extraction unit

For filling and extracting oil from the gearbox, we need to select motor and pump. This motor and pump are selected according to how much oil is to be filled in the gearbox at one time. At first motor is to be selected, we have to dispense 700 ml of oil in the gearbox, and time required should be minimum. By calculations, it is found out that 6 lpm (liters per minute) pump is needed and motor of 0.1 hp with 750 rpm is selected. Now, filters are selected according to the given parameters, here filtration required is up to 10μm microns. Hence we are using two lines of filters with pressure switches and each line has three filters. Three filters are selected with capacities of 60μm, 25μm and 10μm. Hence, the oil which will be obtained at the end of the filtration is 10 μm filtered. Figure 5 shows the working of oil dispensing, filtration and extraction unit.

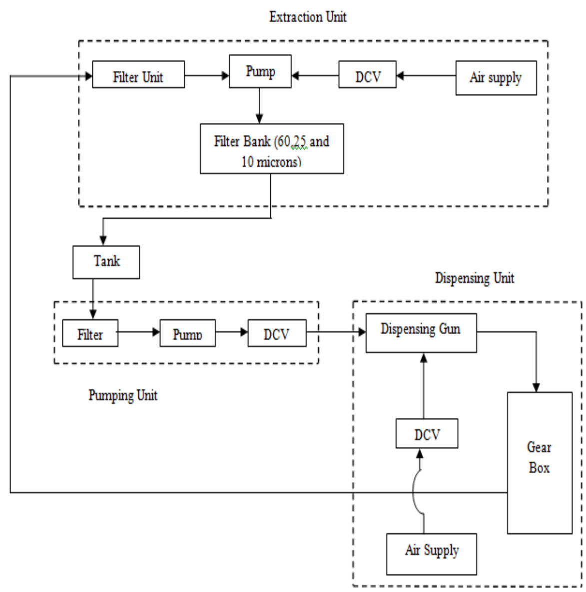


Fig -5: Working of oil dispensing, filtration and extraction unit

5. LOGIC FOR PERFORMING TEST

5.1 Leakage Test

At first the dry leakage test is performed on the gearbox. The type of leakage test is dry leakage test; it will be performed by using air. Leakage is measured by finding pressure drop. If pressure drop is more than allowable value, then gearbox is NOK (not ok) message will display on screen. Pressure drop can be calculated as given below and the input parameters given for measuring pressure drop are given in table 7.

Table -7: Input Parameters for Leakage Test

Parameter	Value	Unit
Leakage rate	15	cc/min
Hold time	10	sec
Volume	2	liter

Leakage rate (cc/min) = [6* allowable pressure drop (mbar) * volume (cc)] / [100* hold time (sec)]..................(a)

Hence, from above formula allowable pressure drop is $1.25*10^{-3}$ mbar. Pressure drops more than this value is not allowed. If pressure drop is more than this value, gear box is not ok message will display on the screen.

5.2 Shift Force Test

Now, the second test will be performed on gearbox. It will be completed in three steps as follows

1) ***First test (assembly test):*** This test will be performed to check gearbox assembly. Here gearbox will run at specific speeds which are given table 8.

Table -8: Input Parameters for 1st test

Gear Shift Operation	Input Speed	Output Torque
	From input shaft	
Neutral- Forward- Neutral	100 rpm	Free
Neutral- Reverse- Neutral	100 rpm	Free

Run the input servo motor shaft of the gearbox at 100 rpm. The output servo motor is running free and at the same time we will check the noise. After 8 sec (settable time), slow down the motor, and wait till motor stops. After rotation speed <50 rpm (settable), we measure the shift force with the help of load cell. If the shift force is less than 15 kgf then OK message will be displaced on the screen else NOK message will be displayed. Noise will be measured with the help of db meter. It should not be more than 40 db. The same test will be performed for neutral to reverse.

2) ***Second test (driving condition):*** This test will be performed to check gearbox in driving condition. Here gearbox will run at specific speeds which are given table 9. Input Servo motors start rotating the input shaft of the gearbox slowly at 1500 rpm. The output servo motors are applying torque limit 6 Nm each. The torque on input servo drive (primary shaft) is recorded. After a delay of 8 sec (settable time), slow down the motor, and wait till motor stops i.e. rotation speed <50 rpm (settable). If the shift force is less than 15 kgf then OK message will be displaced on the screen else NOK message will be displayed. Noise will be measured with the help of db meter. It should not be more than 40 db.

Table -9: Input Parameters for 2nd test

Gear Shift Operation	Input Speed	Output Torque
	From input shaft	Through drive shaft
Neutral- Forward- Neutral	1500 rpm	6 Nm (3 X 2)
Neutral- Reverse- Neutral	1000 rpm	6 Nm (3 X 2)

In reverse position, input servo motors start rotating the input shaft of the gearbox at 1000 rpm. The output servo motors are applying torque limit 6 Nm each. The Torque on input servo drive (primary shaft) is recorded. After a delay of 8 se (settable), slow down the motor, and wait till motor stops i.e. speed <50 rpm (Settable).If the shift force is less than 15 kgf then OK message will be displaced on the screen else NOK message will be displayed. Noise will be measured with the help of db meter. It should not be more than 40 db.

3) ***Third test (dragging condition test):*** This test will be performed to check gearbox in dragging condition. Here gearbox will run at specific speeds which are given table 10. Run the output motor shaft of the gearbox at 500 rpm. The input servo motors are applying torque limit 2 Nm each. The torque on input servo drive (primary shaft) is recorded. After 8 sec. (settable), slow down the motor, and wait till motor stops i.e. speed <50 rpm (settable). If the shift force is less than 15 kgf then OK message will be displaced on the screen else NOK message will be displayed. Noise will be measured with the help of db meter. It should not be more than 40 db.

Table -10: Input Parameters for 3rd test

Gear Shift Operation	Input Speed	Output Torque
	From drive shaft	Through input shaft
Neutral- Forward- Neutral	500 rpm	2 Nm
Neutral- Reverse- Neutral	500 rpm	2 Nm

Now in reverse position, run the output motor shaft of the gearbox at 500rpm. The input servo motors are applying Torque limit 2Nm each. The Torque on input servo drive (primary shaft) is recorded. After 8 sec. (settable), slow down the motor, and wait till motor stops i.e. speed <50 rpm (settable). If the shift force is less than 15 kgf then OK message will be displaced on the screen else NOK message will be displayed. Noise will be measured with the help of db meter. It should not be more than 40 db. After performing all the tests on gearbox and it is showing OK result for each test, we can say that gearbox can be put into desired operation.

5. ANALYSIS OF DESIGNED COMPONENTS

Finite element analysis is performed on fixture, input shaft and output shaft. The results obtained by finite element analysis and analytical calculations are compared and percentage error is calculated. Two analyses are carried on fixture, first one is modal analysis and second one is the structural analysis.

5.1 Modal Analysis of Fixture Plate

Natural frequency of fixture should not co inside with the natural frequency of gearbox. If it co insides, then it will create a resonance, and it should not happen. Hence, here natural frequency of fixture is found out and it is compared with the frequency of gearbox. For doing modal analysis, following boundary conditions are entered Base of the fixture is fixed and density of material is entered 7850 kg/m^3 .Then first three natural frequencies are found out as given in table 11. Gearbox is operating maximum at 3000 rpm i.e. 50Hz. As 265.82 > 50 Hz hence, resonance will not take place. We can say that design is safe.

Table -11: First Three Natural Frequencies

Mode	Frequency (Hz)
1	252.41
2	262.01
3	265.82

5.2 Structural Analysis

1) ***Equivalent stress on fixture:*** The stress distribution on fixture is found out. For doing this analysis meshing and loading conditions on fixture are important. Here the meshing is done using solid hex elements. For better accuracy high mesh quality is used. Figure 6 shows equivalent stress on the fixture when its base is fixed and weight of a gearbox is acting on fixture. By finite element analysis the maximum stress developed on the fixture is $9.32003*10^{-3}$ MPa. This stress value is lower than allowable, hence the design is safe.

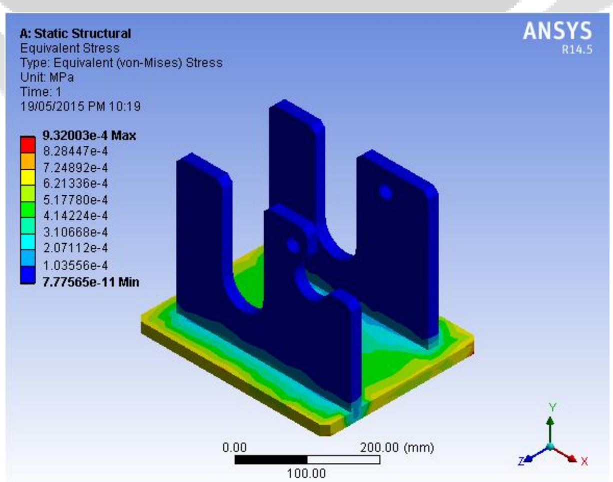
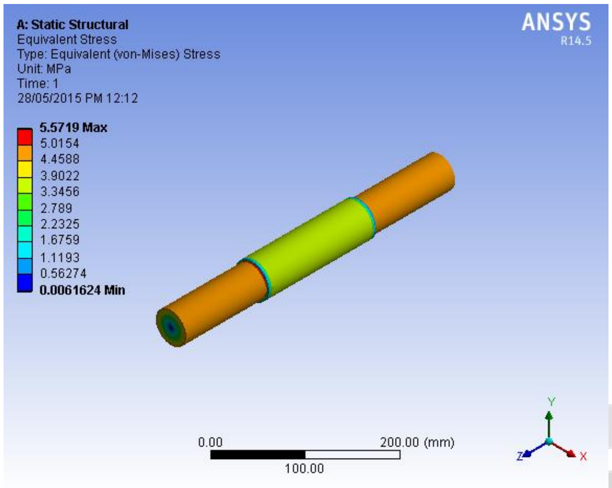


Fig -6: Von-Mises stress on fixture plate



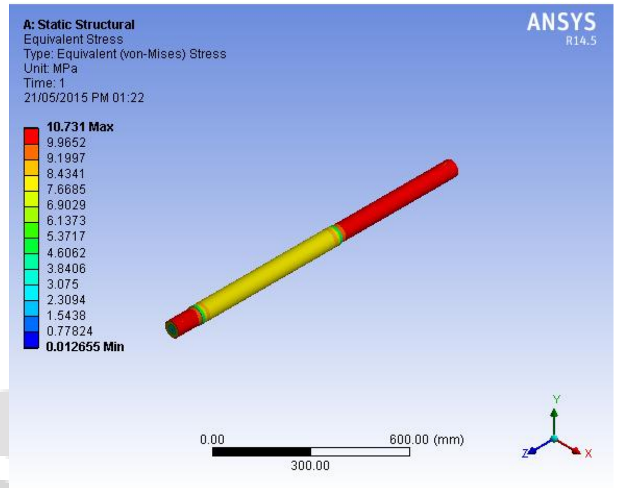


Fig -7: Torsional stress on input shaft

Fig -8: Torsional stress on output shaft

2) ***Torsional analysis of input shaft:*** Torsional analysis on input shaft is carried out. One end of the shaft is fixed and at other end applying moment of 50 kN/mm^2. For meshing solid hex elements are used. Shaft is analyzed for torsional stress. Figure 7 shows torsional stress on input shaft. By finite element analysis maximum torsional stress developed is 5.5719MPa. This value is lower than allowable, hence design is safe.

3) ***Torsional stress on output shaft:*** Torsional analysis on output shaft is done. One end of the shaft is fixed and at other end applying moment of 220 kN/mm^2. For meshing solid hex elements are used. Shaft is analyzed for torsional stress. Figure 8 shows torsional stress on output shaft. By finite element analysis maximum torsional stress developed is 10.731MPa. This value is lower than allowable, hence design is safe.

6. CONCLUSIONS

- The concept of test bench to test given parameters is developed. All the components are designed analytically and finite element analysis is carried out, and there is a good co relation between analytical results and FE analysis results.
- Stress distribution on the fixture is calculated and there is 5.48% error between the analytical and FE result, this error is within the acceptable limit. Hence proposed design of fixture is safe.
- Torsional analysis of input shaft is carried out and there is 2.79% error between the analytical and FE result, this error is within the acceptable limit. Hence proposed design of input shaft is safe.
- Similarly torsional analysis of output shaft is carried out and there is 3.326% error between the analytical and FE result, this error is within the acceptable limit. Hence, proposed design of output shaft is safe.
- Also the modal analysis of fixture is carried out with the help of FE software According to given inputs machine is developed, this machine works with the help of PLC / SCADA system. On this machine we can perform leak test, shift force test in forward condition and in dragging condition, and noise test.

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